TIME OF CONSCIOUSNESS DURING EXPOSURE TO VARIOUS PRESSURE ALTITUDES

by

A. P. Webster
Commander, HS, USNR

and

Orr E. Reynolds
Lieutenant (jg), HS, USNR

7 August 1946

Biodynamics Branch
Research Division
U.S. Bureau of Medicine and Surgery
Navy Department

Table 3

Time of Useful Consciousness and Time to Unconsciousness at Various Altitudes Breathing Air.

Altitude feet	Time of Useful Consciousness sec.	Time to Unconsciousness sec.	Altitude feet	Time of Useful Consciousness sec.	Time to Unconsciousness sec.
25000	198	483	55000	17	27
26000	148	356	56000	17	26
27000	118	281	57000	16	25
28000	97	229	58000	16	24
29000	83	193	59000	16	23
30000	73	167	60000	15	22
31000	64	144	61000	15	21
32000	57	128	62000	15	21
33000	52	114	63000	14	20
34000	47	102	64000	14	19
35000	43	92	65000	14	19
36000	40	84	66000	14	18
37000	37	77	67000	14	18
38000	35	71	68000	13	17
39000	33	65	69000	13	17
40000	31	61	70000	13	16
41000	29	57	71000	13	16
42000	27	53	72000	13	16
43000	26	50	73000	13	15
44000	25	47	74000	12	15
45000	24	44	75000	12	14
46000	23	41	76000	12	14
47000	22	39	77000	12	14
48000	21	37	78000	12	14
49000	20	35	79000	12	13
50000	20	34	80000	12	13
51000	19	32			
52000	19	30			
53000	18	29			
54000	18	28			

CONTENTS

I. INTRODUCTION

For any given set of anoxic conditions, the time of consciousness is identical with the measured time to loss of consciousness. The words time of consciousness then become synomymous with time to unconsciousness. For theoretical and practical reasons the time of consciousness may be considered as composed of two separate and distinct parts: (1) the time of useful consciousness, and (2) the time of non-useful consciousness. The first part represents that conscious time when deliberate and purposeful acts can be successfully carried out; and the second part represents that conscious time when deliberate and purposeful acts cannot be successfully carried out. The sum of these two times, then, is the time of consciousness or the time to unconsciousness.

There are a number of situations and problems in high velocity, high altitude flying where a knowledge of the time of consciousness of individuals exposed to reduced atmospheric pressure may play a role in aircraft design, methods of escape, placement of controls and other mechanisms, etc. For altitudes up to approximately 40,000 feet, knowledge of the time of consciousness is important in event of sudden interruption of oxygen supply, necessitating certain actions on the part of the individual in the useful conscious time available to him. At higher altitudes where pressurized cabins may be used; sudden exposure to the ambient pressure, with or without oxygen supply, by explosive decompression due to failure of the pressurized cabin, will subject the individual to anoxia giving rise to a certain conscious time during which certain acts necessary to his well-being must take place. Knowledge of the time of useful consciousness and the time to unconsciousness in event that bail-out is necessary at high altitude may set the limits beyond which bail-out is impossible--and may be fatal--for a given type aircraft, cockpit design, and bail-out equipment. This paper was written in order to present the available data on time of consciousness at various altitudes; to present a rational theory on time of consciousness at various altitudes to which the rather meager data is fitted; and from which theory, tables and charts were prepared and presented from which the time of consciousness at any altitude may be obtained.

II. NOTATION

$\frac{dw}{dt}$ = rate of transfer of oxygen into or out of the organism.

w = quantity of oxygen transferred in time, t, when the altitude is unchanged.

p_a' = constant pressure of air which will just maintain the oxygen supply to the organism sufficiently to barely maintain consciousness indefinitely, mm.Hg.

p_a = pressure at various altitudes, mm.Hg.

U = overall coefficient of oxygen transfer.

w_1 = quantity of oxygen transferred prior to unconsciousness.

w_2 = quantity of oxygen transferred prior to loss of ability to carry out purposeful acts.

t_1 = time to unconsciousness, sec.

t' = onset of "physiological time", sec.

t_2 = time of useful consciousness, sec.

t_3 = time of non-useful consciousness, sec.

III. THEORETICAL DERIVATION OF RELATIONSHIP BETWEEN CONSCIOUS TIME AND ALTITUDE

It is tacitly assumed that consciousness depends on the maintenance of a given rate of oxygen supplied to the organism. Whether consciousness depends upon supplying this oxygen to the organism as a whole, or to the cerebral cortex, or to any other tissue, is not important to this derivation. The mechanism by which oxygen is transferred and transported within the organism, from the air breathed, is also of no importance in this development.

The major premise is that there is a constant pressure of air (or tension of oxygen) which (when this air is breathed) will just maintain the oxygen supply to the organism sufficiently to barely maintain consciousness at a near threshold level for an indefinite period of time. Let this constant pressure of air be represented by p_a'. It follows, axiomatically, that when the individual is exposed to (breathing) air at a pressure of p_a' or greater, consciousness will be maintained indefinitely.

For any other air pressure, p_a, less than p_a', the rate of transfer of oxygen (out of the organism, probably) is given by:

$$\frac{dw}{dt} = U(p_a' - p_a) \qquad (1)$$

where dw/dt is the rate of transfer of oxygen, and U is the overall coefficient of transfer. The quantity $(p_a' - p_a)$ represents the "driving force". Integration of Equation 1 will give the quantity of oxygen, w, transferred in time, t.

$$\int dw = U(p_a' - p_a)\int dt. \qquad (2)$$

Note that the "driving force", $(p_a' - p_a)$, is a constant for a given altitude. Then

$$w = U(p_a' - p_a)t + C. \qquad (3)$$

To evaluate the constant of integration, C, it is necessary to assume that the starting chronological time does not necessarily correspond with the onset of "physiological time" for this situation. That is,

when $t = 0$, chronologically, $t = t'$, physiologically. It follows that when $t = t'$, $w = 0$, and

$$C = -U(p_a' - p_a)t' \quad \ldots\ldots (4)$$

Whence

$$w = U(p_a' - p_a)(t + t') \quad \ldots\ldots (5)$$

Equation 5 represents the quantity of oxygen, w, transferred in time, t, at a constant altitude pressure, p_a. If the organism becomes unconscious when a given quantity of oxygen, w_1, is transferred, we have

$$w_1 = U(p_a' - p_a)(t_1 + t_1'), \quad \ldots\ldots (6)$$

where t_1 represents the time to unconsciousness at the constant altitude, p_a. If we assume the organism will go unconscious whenever the quantity of oxygen transferred is w_1 regardless of altitude, we obtain the relation between the time to unconsciousness, t_1, at any pressure altitude, p_a:

$$(p_a' - p_a)(t_1 + t_1') = \frac{w_1}{U} \quad \ldots\ldots (7)$$

or

$$(p_a' - p_a)(t_1 + t_1') = K_1 \quad \ldots\ldots (8)$$

and

$$t_1 = \frac{K_1}{p_a' - p_a} - t_1' \quad \ldots\ldots (8a)$$

where

$$K_1 = \frac{w_1}{U}. \quad \ldots\ldots (9)$$

IV. FIT OF THEORETICAL EQUATION (EQUATION 8) TO EXPERIMENTAL DATA

A. Time of Consciousness (Time to Unconsciousness) Versus Pressure Altitude.

Table 1 gives the data obtained from the various references noted in Section VII of this paper for the time of consciousness (time to unconsciousness) at various pressure altitudes.

TABLE 1.

Pressure Altitude, p_a mm.Hg.	Time to Consciousness, t_1, min.	Source No.
34.4	0.25	1
41.4	0.28	1
48.5	0.33	1
56.5	0.38	1
66.2	0.45	1
77.5	0.53	1
123.7	0.83	1
140.0	1.15	2
140.0	0.75	3
168.0	1.33	1
178.7	1.50	3
198.2	2.00	1
225.6	3.00	3
267.4	7.00	6
281.9	5.00	3
281.9	7.30	7
281.9	10.00	6

Figure 1 is a plot of the experimental data from Table 1. on time of consciousness versus pressure altitude. The smooth curve in Figure 1 represents Equation 8 as fitted to the data by an objective, semi-least-squares, method as follows: Equation 8 was expanded, then three simultaneous equations were set up and solved for the three constants: p_a', t', and K.

$$1.\quad p_a' \sum_{1}^{6} t_1 - \sum_{1}^{6} p_a t_1 - t_1' \sum_{1}^{6} p_a + 6(p_a' t_1' - K_1) = 0,$$

$$2.\quad p_a' \sum_{7}^{13} t_1 - \sum_{7}^{13} p_a t_1 - t_1' \sum_{7}^{13} p_a + 7(p_a' t_1' - K_1) = 0,$$

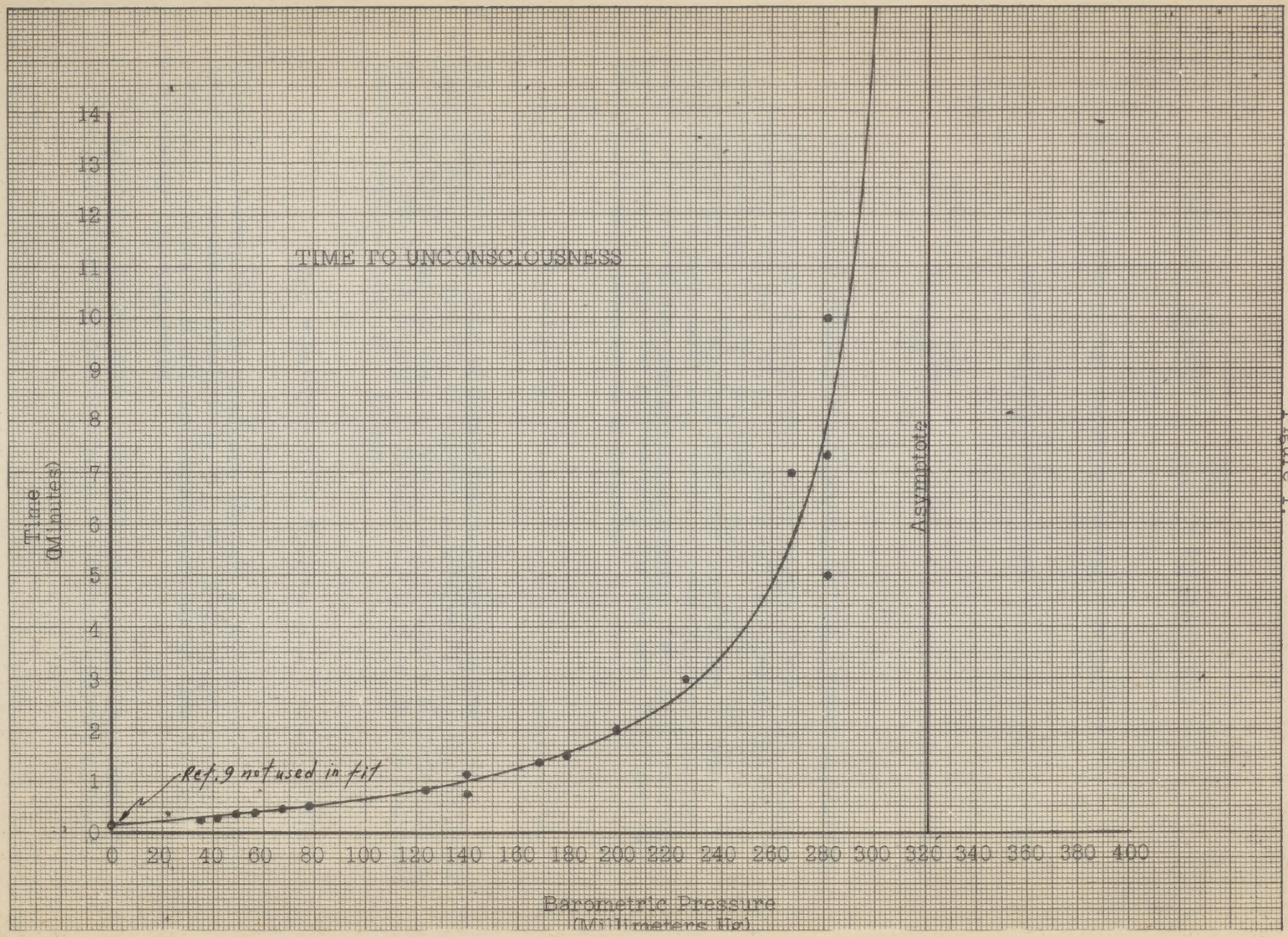

TIME TO UNCONSCIOUSNESS
Time (Minutes)
Asymptote
Ref. 9 not used in fit
Barometric Pressure
(Millimeters Hg)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400

Figure 1.

$$3.\quad p'_a \sum_{14}^{17} t_1 - \sum_{14}^{17} p_a t_1 - t'_1 \sum_{14}^{17} p_a + 4(p'_a t'_1 - K_1) = 0.$$

The equation of the smooth curve thus obtained is

$$(322 - p_a)(t_1 + 0.98) = 361 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

and

$$t_1 = \frac{361}{322 - p_a} - 0.98 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10a)$$

B. Time of Useful Consciousness Versus Pressure Altitude

For practical applications in the design of controls, release mechanisms, and the like, it is convenient to separate the time to unconsciousness, t_1, into two components: t_2, the time of useful consciousness, i.e., that time after the onset of anoxia when deliberate and purposeful acts can be successfully carried out; and t_3, the time of non-useful consciousness when deliberate and purposeful acts cannot be successfully carried out. It follows that the time to unconsciousness is given by

$$t_1 = t_2 + t_3. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Assuming that the point of demarkation between t_2 and t_3 is reached when the quantity of oxygen transferred is w_2, the equation relating time of useful consciousness and pressure altitude may be derived in the same manner as that for the time to unconsciousness versus pressure altitude. Hence

$$(p'_a - p_a)(t_2 - t'_2) = K_2. \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

Theory demands that the pressure altitude at which consciousness would be maintained indefinitely, p'_a, be the same for the two equations, 8 and 12. It will subsequently be shown that the data substantiate this argument.

Table 2 gives the data obtained from the various references for the time of useful consciousness at various pressure altitudes.

TABLE 2.

Pressure Altitude, p_a mm.Hg.	Time of Useful Consciousness t_2, min.	Source No.
140.0	0.50	2
144.8	0.25	4
154.9	0.58	5
178.7	0.77	5
225.6	1.22	5
230.8	1.00	4
267.4	2.00	4
246.9	1.83	5
246.9	2.00	2
281.9	5.00	8
307.4	5.00	4

Figure 2 is a plot of the experimental data of Table 2 on time of useful consciousness versus pressure altitude. The smooth curve of Figure 2 represents Equation 12 fitted in the same manner as the smooth curve of Figure 1. The three simultaneous equations are:

$$1.\quad p_a'\sum_{1}^{4} t_2 - \sum_{1}^{4} p_a t_2 - t_2'\sum_{1}^{4} p_a + 4(p_a' t_2' - K_2) = 0,$$

$$2.\quad p_a'\sum_{5}^{9} t_2 - \sum_{5}^{9} p_a t_2 - t_2'\sum_{5}^{9} p_a + 5(p_a' t_2' - K_2) = 0,$$

$$3.\quad p_a'\sum_{10}^{11} t_2 - \sum_{10}^{11} p_a t_2 - t_2'\sum_{10}^{11} p_a + 2(p_a' t_2' - K_2) = 0.$$

The resulting equation for the smooth curve thus obtained is

$$(322 - p_a)(t_2 + 0.28) = 143. \quad \text{..... (13)}$$

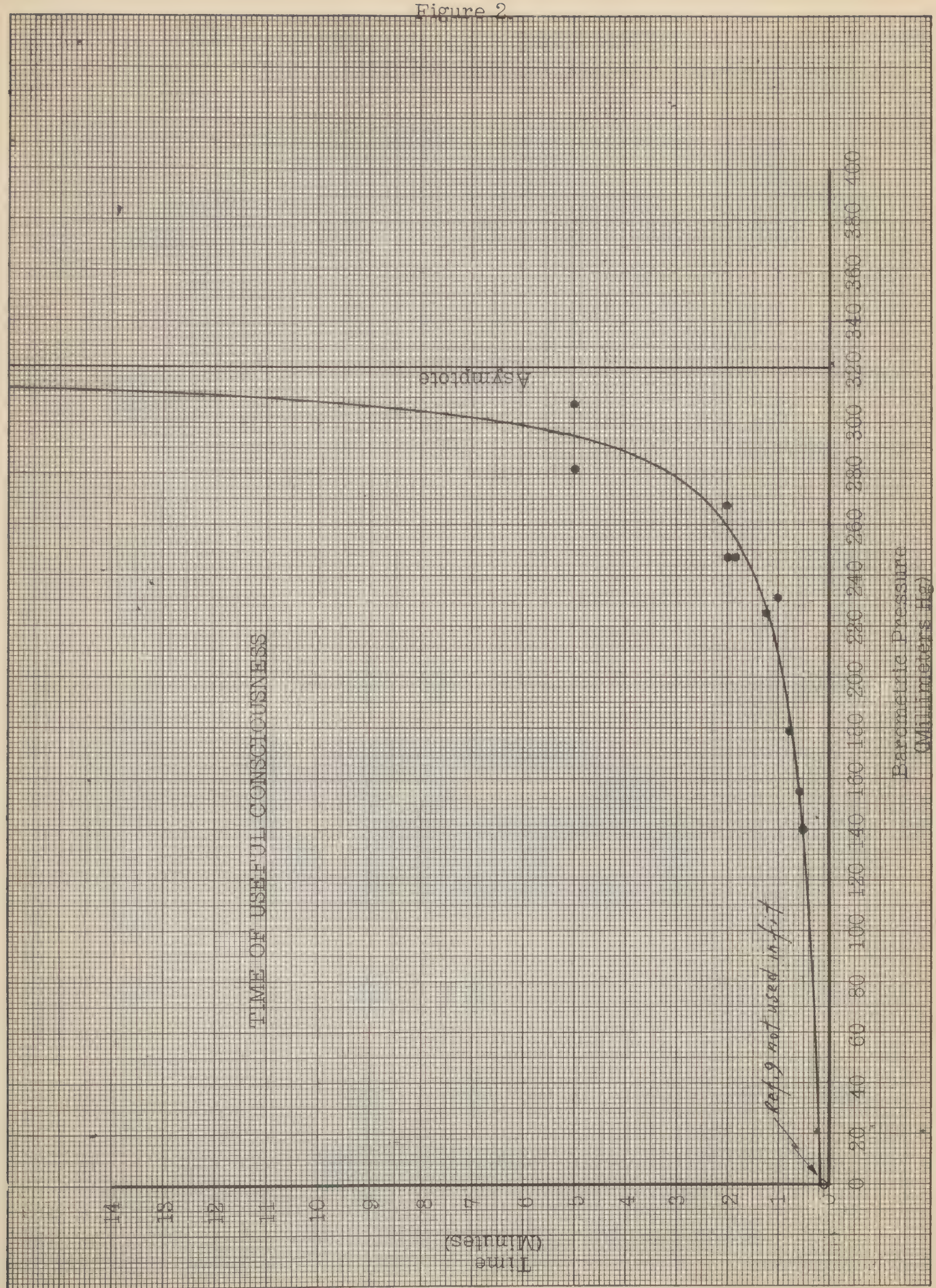
and

$$t_2 = \frac{143}{322 - p_a} - 0.28. \quad \text{..... (13a)}$$

Note that p_a' in equations 10 and 13 for time to unconsciousness and time of useful consciousness is given as 322 millimeters of mercury. Actually, in the solution of the three simultaneous equations for the two situations, we obtained 321.84 and 321.63. Thus, the theory which demands that p_a' be a constant is substantiated by the data.

Two points (reference 9) representing the time of consciousness after arrest of cerebral circulation are shown on the graphs, but were not used in fitting the experimental data to the theory.

Figure 2


TIME OF USEFUL CONSCIOUSNESS
Asymptote
Ref. 9 not used in fit
Barometric Pressure
(Millimeters Hg)
Time
(Minutes)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

V. APPLICATIONS OF EQUATIONS 8a AND 12a

A. Non-Useful Consciousness Versus Pressure Altitude.

The time of non-useful consciousness, t_3, is given by Equation 11 as the difference between the time to unconsciousness, t_1, and the time of useful consciousness, t_2. Subtracting Equation 12a from Equation 8a, we have

$$t_3 = t_1 - t_2 = \frac{(K_1 - K_2)}{p_a' - p_a} - (t_1' - t_2'), \quad \text{..... (14)}$$

from which

$$t_3 = \frac{K_3}{p_a' - p_a} - t_3', \quad \text{..... (15)}$$

where

$$K_3 = K_1 - K_2, \quad \text{..... (16)}$$

and

$$t_3' = t_1' - t_2'. \quad \text{..... (17)}$$

Equation 15 for non-useful consciousness is the same form as Equations 8a and 12a, all three equations being hyperbolas having the common asymptote, p_a', indicating the constant pressure altitude at which consciousness is maintained indefinitely; and three separate time asymptotes, t_1', t_2', and t_3', indicating the physiological onset of the particular phenomena. The equation for non-useful consciousness versus pressure altitude with the numerical constants inserted is then

$$(322 - p_a)(t_3 - 0.70) = 218, \quad \text{..... (18)}$$

and

$$t_3 = \frac{218}{322 - p_a} - 0.70. \quad \text{..... (18a)}$$

B. Relation Between Time of Useful Consciousness and Time to Unconsciousness.

Eliminating the pressure altitude, p_a, between Equations 10a and 13a, we obtain

$$t_2 = 0.396\, t_1 + 0.108 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

as the relation between time of useful consciousness and time to unconsciousness. Note that this expression is linear and that the time of useful consciousness is approximately four tenths the time to unconsciousness for all pressure altitudes. Equation 19 is plotted in Figure 3.

C. Time to Unconsciousness on Air and Oxygen Versus Altitude in Feet.

Equation 10a is plotted in Figure 4, replacing the pressure altitude, p_a, by the appropriate altitude in feet as obtained from the National Advisory Committee for Aeronautics, Report No. 218, "Standard Atmosphere - Tables and Data", by Walter S. Diehl. Also, in Figure 4, the time to unconsciousness is plotted in seconds. Figure 4 then gives the time to unconsciousness in seconds versus the altitude in feet.

In order to obtain the curve for exposure to one hundred per cent oxygen, rather than air, it was necessary to obtain a relationship between altitudes breathing air and altitudes breathing oxygen. This relationship was obtained from the curve for equivalent altitudes, Chart A-2, "Handbook of Respiratory Data in Aviation", CAM and CMR, 1944. The equation derived from this chart is

$$h_{1.000} = 0.6h_{.209} + 33{,}800 \text{ feet}, \quad \ldots\ldots\ldots\ldots\ldots \quad (20)$$

where $h_{1.000}$ is the altitude breathing oxygen which is equivalent to the altitude breathing air, $h_{.209}$. By plotting the time to unconsciousness corresponding to $h_{.209}$ against $h_{1.000}$ as obtained from Equation 20, the curve for time to unconsciousness against altitude when breathing oxygen was obtained in Figure 4.

D. Time of Useful Consciousness on Air and Oxygen Versus Altitude in Feet.

Equation 13a is plotted in Figure 5 replacing the pressure altitude, p_a, by the appropriate altitude in feet, the time in seconds, and the appropriate altitude breathing oxygen in the same manner as the curves of Figure 4 were prepared.

Note that in the equations for time to unconsciousness and time of useful consciousness, the pressure altitude at which consciousness may be expected to last indefinitely (in the average individual)

breathing air is 322 millimeters of mercury, corresponding to 21,913 feet, and the altitude at which consciousness may be expected to last indefinitely breathing oxygen is 46,948 feet, corresponding to a pressure altitude of 101 millimeters of mercury.

E. Time of Useful Consciousness Versus Time to Unconsciousness Breathing Oxygen.

This relationship is given by Equation 19 in which the times are those breathing oxygen.

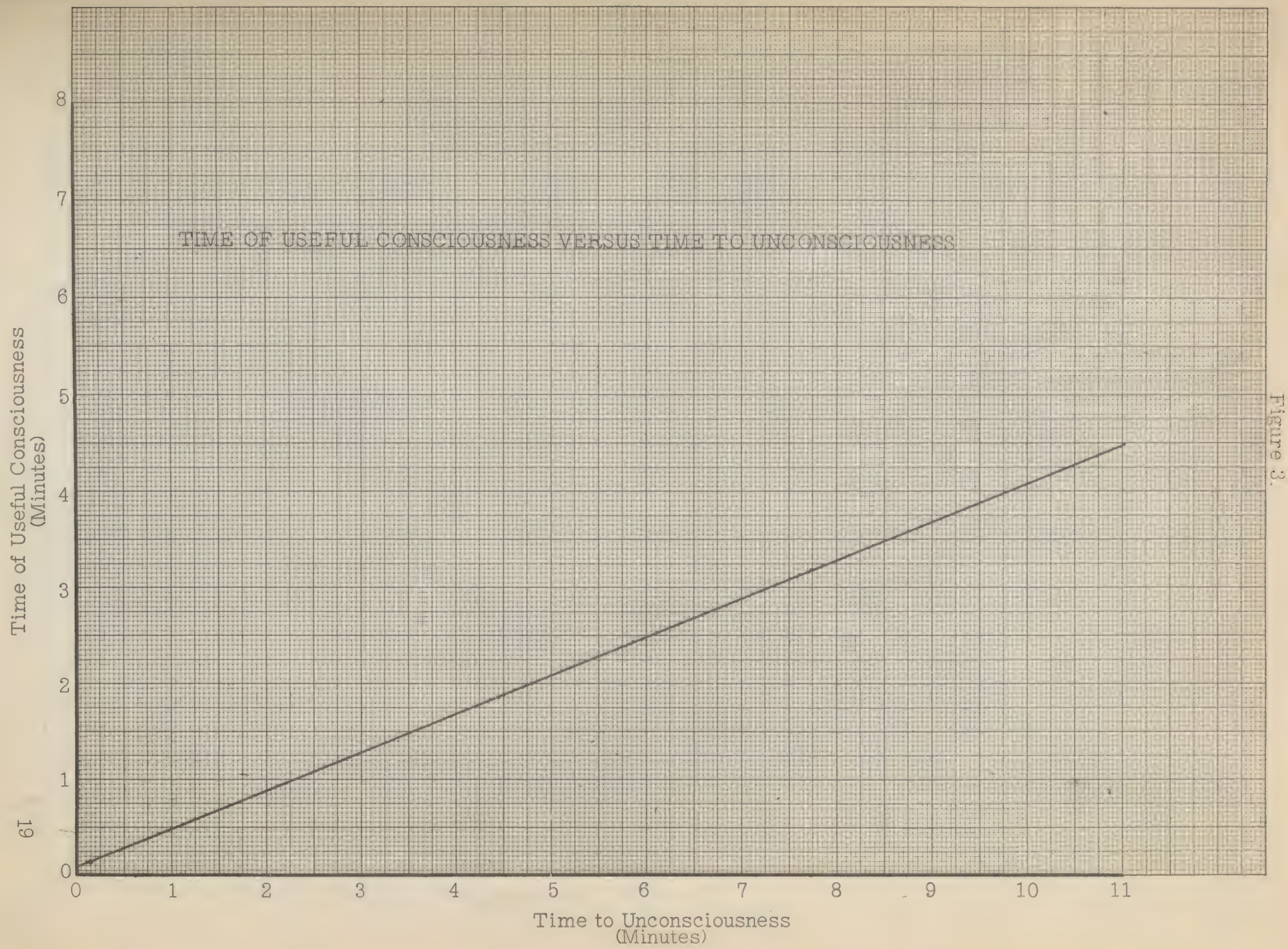

TIME OF USEFUL CONSCIOUSNESS VERSUS TIME TO UNCONSCIOUSNESS
Time of Useful Consciousness (Minutes)
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
7
8
9
10
11
Time to Unconsciousness (Minutes)

Figure 3.

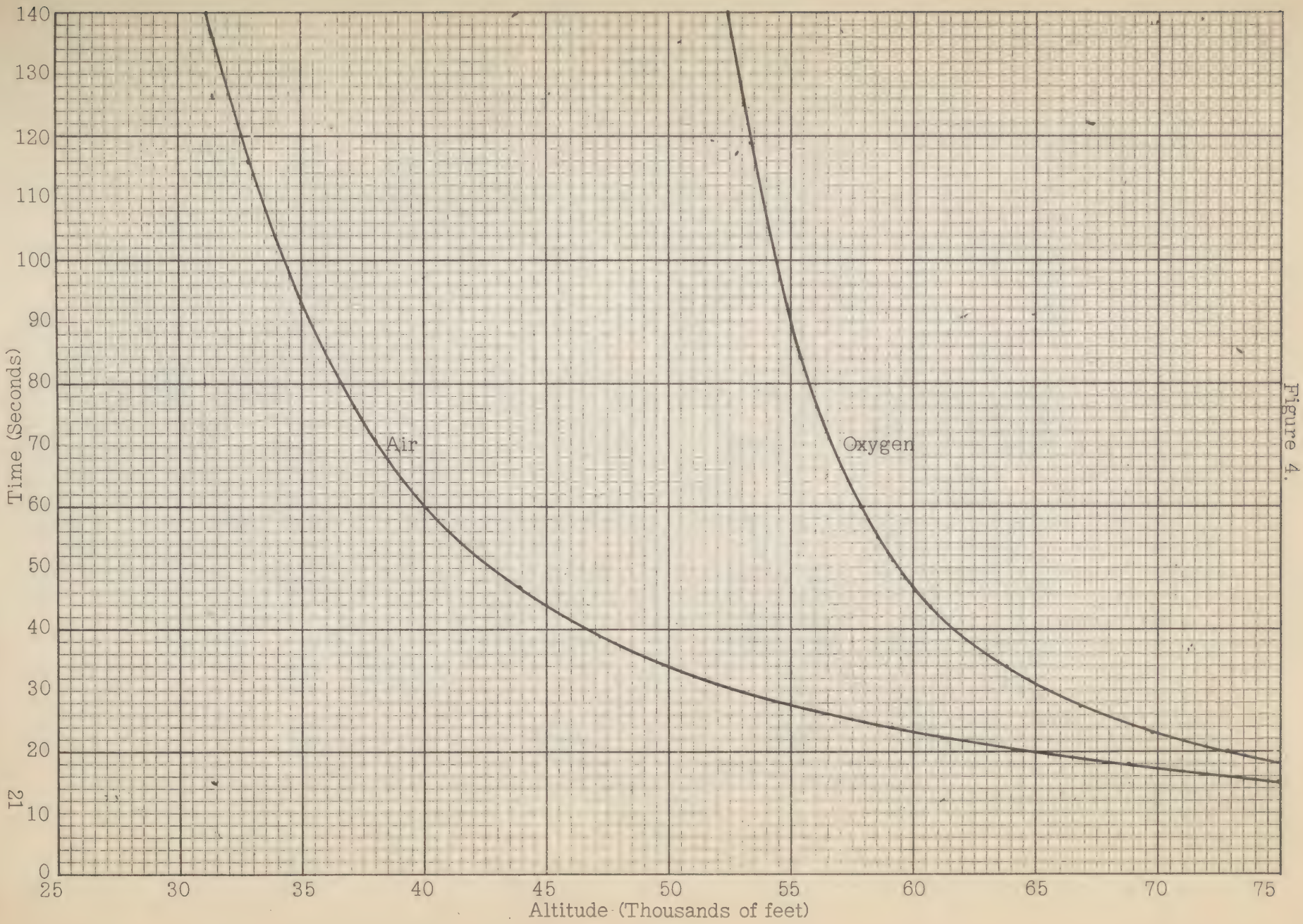

TIME TO UNCONSCIOUSNESS
Time (Seconds)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
21
Air
Oxygen
25
30
35
40
45
50
55
60
65
70
75
Altitude (Thousands of feet)

Figure 4.

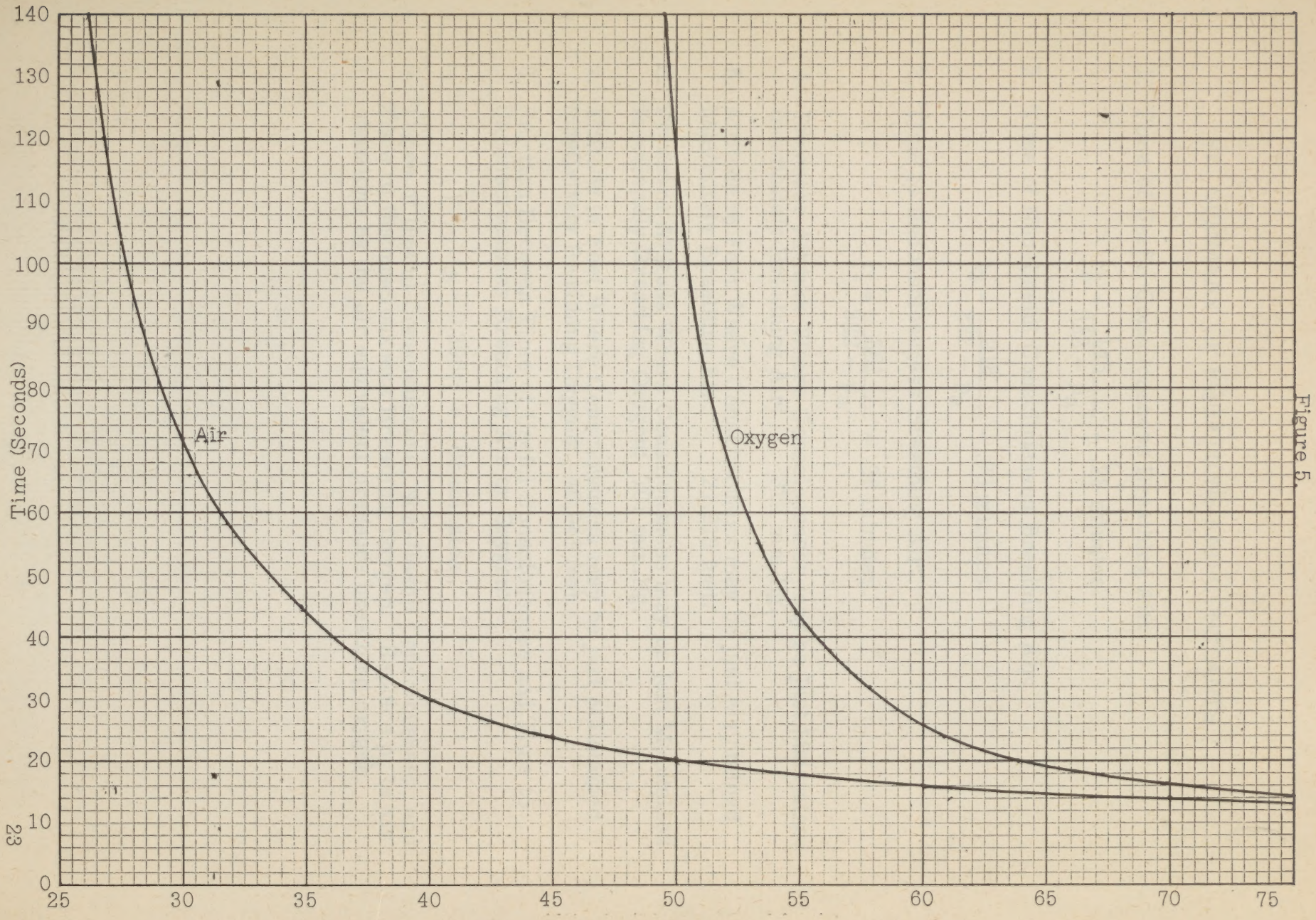
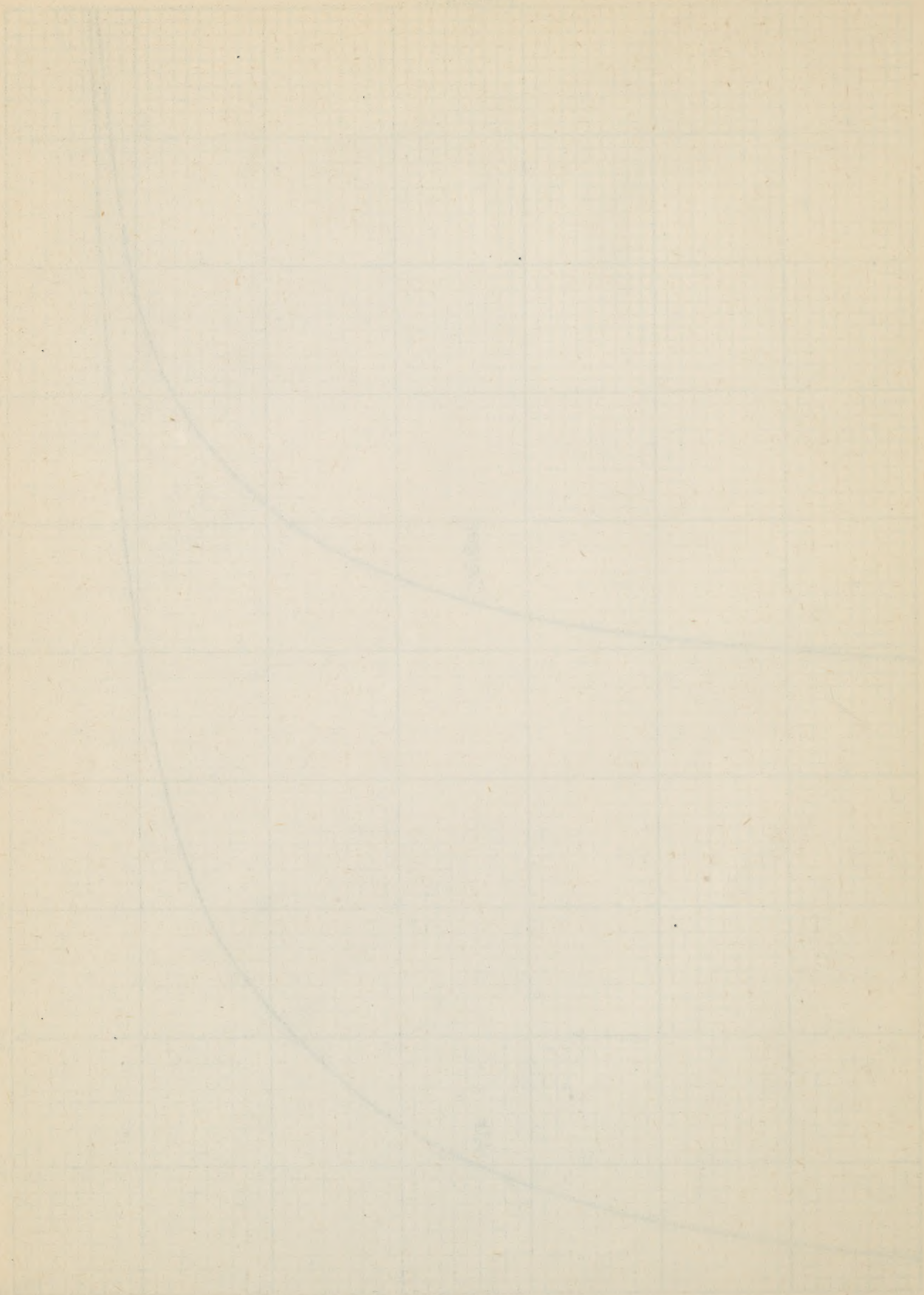

TIME OF USEFUL CONSCIOUSNESS
Time (Seconds)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
25
30
35
40
45
50
55
60
65
70
75
Air
Oxygen

Figure 5.



VI. SUMMARY OF EQUATIONS AND CONSTANTS

1. Time of Useful Consciousness Breathing Air:

$$t_2 = \frac{143}{322 - p_a} - .28 \text{ minutes.}$$

2. Time of Non-Useful Consciousness Breathing Air:

$$t_3 = \frac{218}{322 - p_a} - .70 \text{ minutes.}$$

3. Time to Unconsciousness Breathing Air:

$$t_1 = \frac{361}{322 - p_a} - .98 \text{ minutes.}$$

4. Pressure Altitude Where Consciousness may be Just Maintained Indefinitely Breathing Air: 322 mm.Hg.

5. Altitude in Feet Where Consciousness may be Just Maintained Indefinitely Breathing Air: 21,913 feet.

6. Pressure Altitude Where Consciousness may be Just Maintained Indefinitely Breathing Oxygen: 101 mm.Hg.

7. Altitude in Feet Where Consciousness may be Just Maintained Indefinitely Breathing Oxygen: 46,948 feet.

8. Relation Between Time of Useful Consciousness and Time to Unconsciousness Breathing Air or Oxygen:

$$t_2 = 0.396t_1 + .108 \text{ minutes.}$$

9. Times of Useful Consciousness, Non-Useful Consciousness, and Time to Unconsciousness Breathing Oxygen: Replace p_a in air equations by the air equivalent pressure breathing oxygen.

VII. SOURCE OF DATA

1. Rasher, S. Experiments at Dachau. Communication to Medical Liaison Officer, Military Requirements Division, BuAer, Navy Department, from Lieutenant Commander A. H. Andrews, Jr., 17 October 1945.

2. Barry, Alexander. Emergency Descent from Altitude. U.S. AAF, Materiel Command, Engineering Division, Memorandum Report, 5 February 1946.

3. Evelyn, Kenneth. The Effects of Low Barometric Pressure on the Health of the Adult Male in the Age Group 19 - 32. National Research Council, Division of Medical Science, Committee on Aviation Medicine, Report No. 19, 3 July 1941.

4. Aero Medical Exploitation by AAF, Germany, 1945. Studies by Tavel.

5. Hoffman, C. E., Clark, R. T., Jr., and Brown, E. B., Jr. The Rates of Fall of Blood Oxygen Saturations at Simulated Altitudes Following Mask Removal; Period of Useful Consciousness and Time to Imminent Unconsciousness Following Change from 100% Oxygen to Ambient Air at Altitudes Above 28,000 Feet. BuMed Research Project No. X-572, 1 December 1945.

6. Commoner, Barry. Voluntary Pressure Breathing of Ambient Atmosphere as a Means of Increasing the Oxygen Saturation of the Blood. BuMed Research Project No. X-198, 19 October 1943.

7. Houston, Charles S. U.S. Naval Air Station, Miami, Florida. Communication to Research Division, BuMed, Navy Department, 22 September 1944.

8. Bachrach, William H. Communication to Research Division, BuMed, Navy Department, February 1946.

9. Rossen, R., Kabot, H. and Anderson, J. Acute Arrest of Cerebral Circulation in Man. Arch. Neurol. and Psychiat. 50:510-528, November 1943.